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A TRAC-PD2 ANALYSIS OF FLECHT EXPERIMENTS*

by

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ABSTRACT

This report describes TRAC-PD2 calculations of FLECHT (Full Length Emergency Cooling Heat Transfer) tests 4831 and 17201. The calculations were performed as part of the TRAC-PD2 developmental assessment where our objective was to assess TRAC-PD2 reflood modeling under forced flooding conditions. We compared calculated and experimental values for peak fuel-rod clad temperature, clad quenching time, and rod bundle effluent rates; and performed calculations with an approximate radiation heat-transfer model added to the basic TRAC-PD2 code. Our findings demonstrate the potential importance of surface-to-surface radiation heat transfer in these tests.

I. INTRODUCTION

In this paper we present comparisons of TRAC-PD2 (Ref. 1) calculations and experimental results for FLECHT (Full Length Emergency Cooling Heat Transfer) cosine test 4831 (Ref. 2) and FLECHT low flooding rate test 17201 (Ref. 3). These calculations were performed as a part of the TRAC-PD2 developmental assessment problem set where the principal objectives are to assess the validity of the physical models, correlations, and numerical methods used in TRAC-PD2 over a wide range of applications. A corollary objective is to suggest improvements to the code, which will enhance its applicability or accuracy.

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In the FLECHT-series calculations, particular emphasis was placed on the ability of TRAC-PD2 to predict peak fuel-rod clad temperature and quenching time. In addition, liquid mass carryover rates were examined. In all analyses the released standard version of TRAC-PD2 was utilized except where noted.

II. DESCRIPTION OF TRAC-PD2 CODE

TRAC-PD2 is a best-estimate computer code developed for the analysis of large-break, loss-of-coolant accidents (LOCAs). The code is applicable to a wide range of other light-water reactor accidents and has been successfully utilized to analyze the first three hours of the Three Mile Island accident.[4] Because TRAC-PD2 has been described in detail elsewhere,[1] only a brief description is given here.

TRAC-PD2 is a systems code, joining detailed models of reactor components to construct the overall system of interest. TRAC-PD2 has modules for vessel, pressurizer, steam generator, pipe, tee, pump, accumulator, and valve components, as well as fill and break modules for modeling system boundaries. Using these component modules, a wide variety of systems can be modeled. All the models except the vessel are one-dimensional, using a drift-flux hydrodynamics model. The vessel uses a full three-dimensional, two-fluid hydrodynamics formulation to model potentially important three-dimensional flow patterns in the reactor vessel.

The overall structure of the code is highly modular, with separate sections performing input, initialization, output, and calculational functions. The thermal-hydraulics calculations are themselves divided into preparatory, iterative, and updating segments with a special segment for evaluating the convergence of steady-state calculations.

The numerical solution to the hydrodynamics equations is effected through linearization of the differential equations, conversion to finite-difference form, and iterative solution by a Newton-Raphson technique. Both semi-implicit and fully implicit finite-difference formulations are available for one-dimensional components, while only the semi-implicit solution technique is used for the three-dimensional vessel. The semi-implicit technique imposes a "material Courant" time step stability limit of approximately

$$\Delta t \leq \text{Min} \left| \frac{h}{V} \right| ,$$

where h is the grid spacing dimension and V is the local fluid velocity. To avoid overly restrictive conditions near breaks or nozzles, the fully implicit scheme is used in these components.

In summary, TRAC-PD2 is a very sophisticated and flexible modular systems code capable of effectively calculating the behavior of a wide range of problems.

III. A BRIEF DESCRIPTION OF THE FLECHT EXPERIMENTS

The FLECHT program is a series of reflood heat-transfer simulation experiments designed to provide separate effects data for use in pressurized water reactor (PWR) emergency core cooling (ECC) system heat-transfer evaluation. Two of these tests, representing a range of test conditions, were chosen for inclusion in the TRAC-PD2 assessment problem series. Test 4831 used a low flooding rate (1.5 in./min) with an axial cosine power shape rod bundle, while test 17201 used a higher flooding rate (6.0 in./min) with a skewed axial power profile.

The operating procedures for both tests were similar. The lower plenum of the test vessel housing was filled with water to the bottom of the heated rod length. Electrical power was supplied to the simulated control rods until the desired initial rod-cladding temperatures were attained. Then flooding at the specified rate was initiated while rod power was decreased according to the desired decay curve. Rod-cladding temperatures and a number of fluid conditions were recorded until the bundle was completely quenched.

Test 4831 was conducted with a rather massive, square rod bundle housing. A square rod bundle with 100 full-scale nuclear fuel-rod simulators was placed in the housing. Ninety-one of these rods were electrically heated with a step-wise approximation to an axial cosine power profile. Some radial power variation was included with a variation of 0.95 to 1.1 of average rod power across the rod bundle.

Because of housing mass effects in earlier tests, a cylindrical, low mass housing was designed for use in subsequent FLECHT tests. Test 17201 was conducted using this newer geometry. In these tests the rod bundle consisted of 105 heated rods with seven unheated thimbles for instrumentation and solid spacers to reduce the flow area. Again a radial power profile was simulated. In these tests, however, the axial power profile was skewed toward the top of the heated section.

Liquid effluents from the flooding test were separated and collected in a carryover tank, while the dry steam was exhausted to the atmosphere through a flow measuring orifice. This allowed measurement of liquid carryover and vapor flow from the core. In addition, a series of differential pressure cells provided an approximate void fraction profile of the test section. Thermocouples provided rod-cladding and housing-temperature measurements. Most of this data was recorded on a data acquisition system, which provided the graphical time history plots used in TRAC data comparisons.

IV. TRAC-PD2 MODELS

The FLECHT tests were modeled for TRAC-PD2 by using a constant velocity fill for ECC flooding water injection, which was connected by a short pipe to the lower plenum of the vessel. An effluent pipe connected the upper vessel plenum with a constant pressure break, which modeled the carryover tank. The vessel was divided into 13 axial levels to facilitate modeling of the rod axial power profile; this model is illustrated in Fig. 1. This noding did necessitate some interpolation of measured initial rod-cladding temperatures and hence some slight disagreement between measured and input initial temperatures at a few points. The axial power distribution modeled in TRAC for test 4831 is compared to the experimental values in Fig. 2. The housing walls were modeled using heat slabs in the TRAC vessel component.

The TRAC calculational sequence followed the test procedure closely. The problem began with the lower plenum full and the rods at their initial temperatures. The FILL component was then turned on to simulate forced flooding. The calculation continued until all rods had quenched according to clad temperature-time plots.

V. TRAC CALCULATIONAL RESULTS

The principal parameters compared in the FLECHT assessment set were clad temperatures vs time and carryover rates into the moisture separator. These comparisons gave an indication of the accuracy of the reflood and entrainment models in TRAC-PD2.

In general, TRAC-PD2 clad temperatures tended to peak late and quench late. One possible cause of this systematic discrepancy is radiative heat transfer from rod to rod and rod to housing. This can be an important effect, accounting for 25-30% of the total heat transfer in some cases.[5] An approximate radiative heat-transfer model was placed in a special version of TRAC-PD2 to scope the effect of such phenomena. These calculations, based on a surface-to-surface radiative heat-transfer model, indicated that modeling such an effect could account for much of the discrepancy in quench time between the calculation and the test.

Figures 3 and 4 illustrate clad temperature traces for two levels in test 17201. At each level the clad temperature peaks at a higher value than the test data. This could be caused by radiation effects, because the calculated temperature peaks later than in the data. Another possible source of discrepancy could be uncertainties in the precooling rate due to the carry-over or in steam precooling models. After peak temperature, the TRAC-PD2 temperature traces usually show a rod cooldown rate a little above the test data. Calculated quench times tend to be 30-40 s after the test data, with the highest elevations having the largest discrepancies. At most levels, TRAC-PD2 predicted a quench temperature close to the test data for test 17201.

Figures 5 through 7 illustrate clad temperatures for several important elevations in test 4831. Again, the calculated clad temperatures peak late and quench late. The effect of radiation and the difference between the calculated and experimental quench temperatures can readily account for this discrepancy.

Test 4831 was also analyzed by using the previous TRAC version, TRAC-P1A. These results are included in Figures 5 through 7 for comparison with the TRAC-PD2 calculations. TRAC-P1A quench times are much earlier than either the experimental or TRAC-PD2 values at higher core elevations, but the quench temperature is about the same in both TRAC-PD2 and TRAC-P1A at these levels. Calculated quench temperatures are considerably lower than in the experimental data for all levels above the core midplane. At the midplane, a proper calculation of the quench temperature would result in nearly exact prediction of the quench time for TRAC-PD2, with inclusion of radiation effects probably resulting in early quench prediction.

Total effluent mass flow rates calculated by TRAC-PD2 agree very well with test data in both FLECHT tests. Figure 8 shows a comparison of data and calculation for test 4831. Greater care is required in analyzing the data from Test 17201. In this test a large amount of water that was carried out of the core was "stored" in the upper plenum and thus does not show up in the measured effluence. TRAC-PD2 does not model this upper plenum storage, but the total effluence from the core, found by including the mass stored in the upper plenum and that collected in the carryover tank, agrees well with that calculated by TRAC-PD2. This does not directly indicate an acceptable entrainment model. In fact, for much of the TRAC-PD2 calculation, the two-phase mixture that reaches the upper plenum is virtually dry steam, with most of the liquid having either evaporated or fallen back into the vessel. The liquid mass flow rate does indicate a number of slugs of liquid are ejected throughout the course of the transient. The integrated liquid mass ejected is about 70 kg at 350 s according to the calculation. The experimental liquid effluent, including mass stored in the steam probes and upper plenum, is 72.6 $\pm$ 10.8 kg. The mass flow rate indicated in the test data is smoother than the TRAC-PD2 calculation, but the integrated results are remarkably close.

The TRAC-PD2 calculations for both FLECHT assessment problems compare quite well with the test data, indicating for this case that TRAC-PD2 uses reasonable reflood and entrainment models.

VI. RADIATIVE HEAT-TRANSFER MODEL

Radiation effects such as those encountered in the FLECHT experiments are not expected to be significant in the pressurized water reactor calculations for which TRAC-PD2 is intended. Therefore, TRAC-PD2 does not contain a surface-to-surface radiative heat-transfer model. This heat-transfer mechanism has been shown, however, to have a significant effect on FLECHT quench times.[5] TRAC-PD2 predictions of the FLECHT quench times generally are late, indicating that the heat flux from the simulated fuel rods is underpredicted.

To determine the importance of radiative heat transfer to TRAC reflood predictions, a simple radiative heat-transfer model, described below, was implemented in TRAC. (This model is not in the released version of the code.)

The radiative heat-transfer model used in TRAC includes a hot rod, a cold rod modeling the instrument thimble, and the surrounding channel wall, as shown in Fig. 9. The governing equations for surface-to-surface radiative heat transfer are given by Sparrow and Cess[6] as

$$B_i = \epsilon_i \sigma T_i^4 + (1-\epsilon_i) \sum_{j=1}^{N} B_j F_{ij} \tag{1}$$

and

$$\frac{Q_i}{A_i} = \frac{\epsilon_i}{1-\epsilon_i} (\sigma T_i^4 - B_i) \quad , \tag{2}$$

where

B_i = radiosity of surface i,
ϵ_i = emissivity of surface i,
T_i = temperature of surface i,
N = the number of surfaces,
F_{ij} = fraction of energy leaving surface i that reaches surface j (view factor),
Q_i = heat transfer from surface i, and
A_i = area of surface i.

In Eq. 1, it is assumed that the surface temperatures, the emissivities, and the view factors are known. The surface temperatures from the previous time step were used in the present analysis.

Nine view factors, F_{ij}, are needed for the geometry shown in Fig. 9. For adjacent rods of the same diameter, an analytical expression exists for the view factor. Adjusting the half-circle results of Ref. 6 to a full cylinder gives

$$F_{12} = \left[\frac{1}{\pi} \sqrt{X^2 - 1} - X + \frac{\pi}{2} - \cos^{-1}\left(\frac{1}{X}\right) \right] , \tag{3}$$

where X = pitch/diameter.

The remaining view factors can be found by using the reciprocity rule

$$A_i F_{ij} = A_j F_{ji} \tag{4}$$

and by using conservation of energy[6]

$$\sum_{j=1}^{N} F_{ij} = 1 \ . \tag{5}$$

For the present geometry, the pitch to diameter ratio is 1.336. The view factors are given in Table I. The surface emissivities are given in Table II.

TABLE I

VIEW FACTORS

	i		
j	1	2	3
1	0.0	0.1260	0.8740
2	0.1260	0.0	0.8740
3	0.0674	0.0674	0.8652

TABLE II

SURFACE EMISSIVITIES

Surface Number	Emissivity
1	0.90
2	0.90
3	0.96

The thimble temperatures as functions of time were taken from Ref. 7 and are shown in Table III.

TABLE III

THIMBLE TEMPERATURES AS A FUNCTION OF TIME

Time (s)	Thimble Temperature (K)
0.0	800.0
25.0	600.0
50.0	500.0
75.0	400.0
160.0	400.0

The channel wall temperature was maintained at a constant 405 K.

Equations (1) and (2) were solved for the heat flux leaving each surface, and the rod surface boundary condition in TRAC was modified to include the radiative heat flux as well as the convective heat flux. The effect of this model on TRAC predictions is discussed in Sec VII.

VII. RESULTS OF CALCULATION WITH RADIATION

Test 17201 was calculated by TRAC-PD2 using the approximate radiation model described in Section VI. We found that the incorporation of this model had a major effect on the calculated peak temperature and the quench times. In Figures 10 and 11 experimental data for representative rod temperature traces are compared with calculations using standard TRAC-PD2 and TRAC-PD2 with the radiation model. One readily noted feature of the traces with radiation modeling is a flattening of the peak rod temperature. The standard TRAC-PD2 tends to overpredict significantly the temperature rise in test 17201, with the temperature peak occurring later than in the test data. With radiation modeling, however, no perceptible temperature rise occurs in the calculation, but a nearly flat trace persists for some time after test initiation. Finally, precooling caused by vapor and entrained liquid apparently becomes significant and rather rapid cooldown results. Thus, TRAC-PD2 may underpredict precooling in the early stages of the transient, at least for axial levels above the midplane.

Once cooldown begins, the rod cooldown rate is initially slightly higher with the radiation model, but both calculated cooldown rates decrease near the quench temperature to a value less than that of the experimental data.

The TRAC-PD2 quench temperature is close to the data in both calcula- tions but the calculation with radiation modeling quenches much closer to the experimental quench time than with the standard TRAC-PD2.

In summary, the radiation model described above was placed in TRAC-PD2 to approximate radiative heat transfer in FLECHT. This model did essentially eliminate the excessive rod temperature peaking observed in standard TRAC-PD2 calculations. In fact, radiation was probably overpredicted to the point that the small temperature peak observed experimentally was not calculated. The radiation calculation did indicate an underprediction of precooling early in the transient, however, followed by a reasonably accurate cooldown rate and a quench near the right temperature and time. Thus radiation effects can account for most of the discrepancy between TRAC-PD2 calculations and FLECHT data, with precooling effects potentially contributing to a lesser extent.

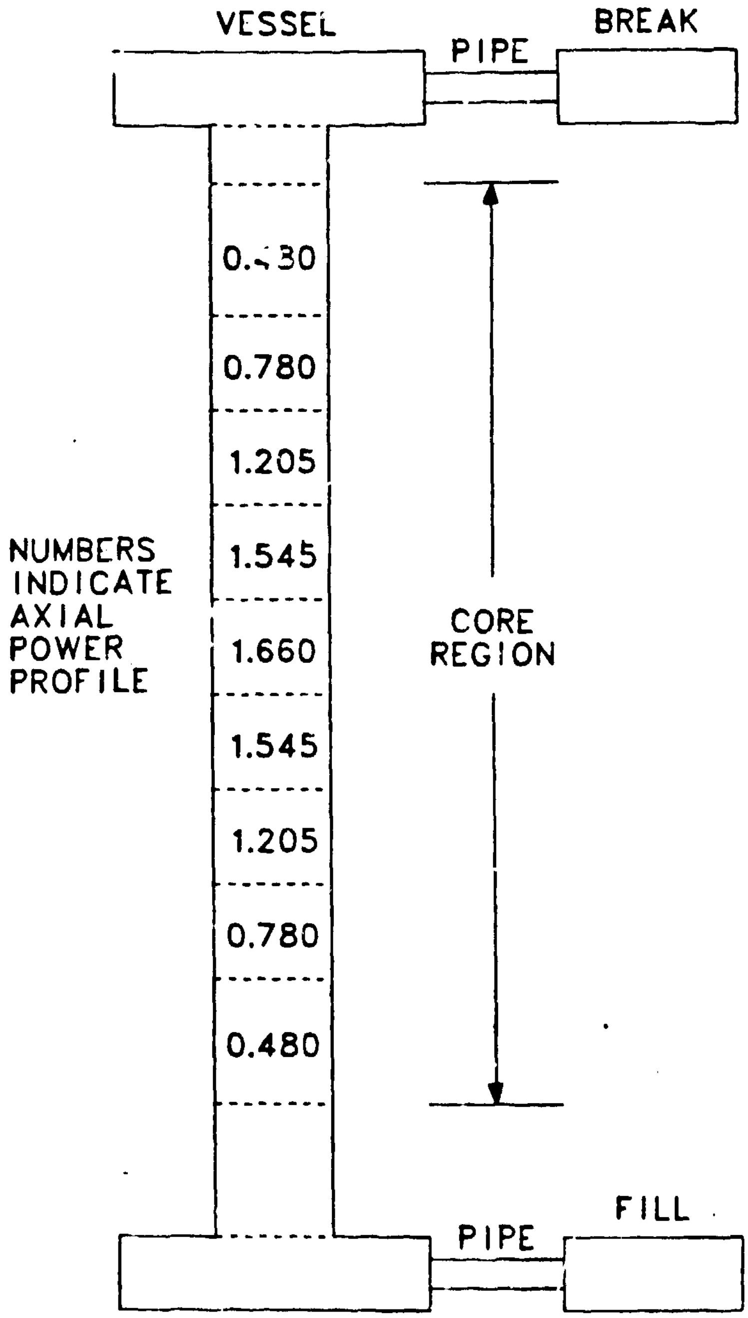

Fig. 1. TRAC-PD2 noding scheme for FLECHT forced flooding experiments.

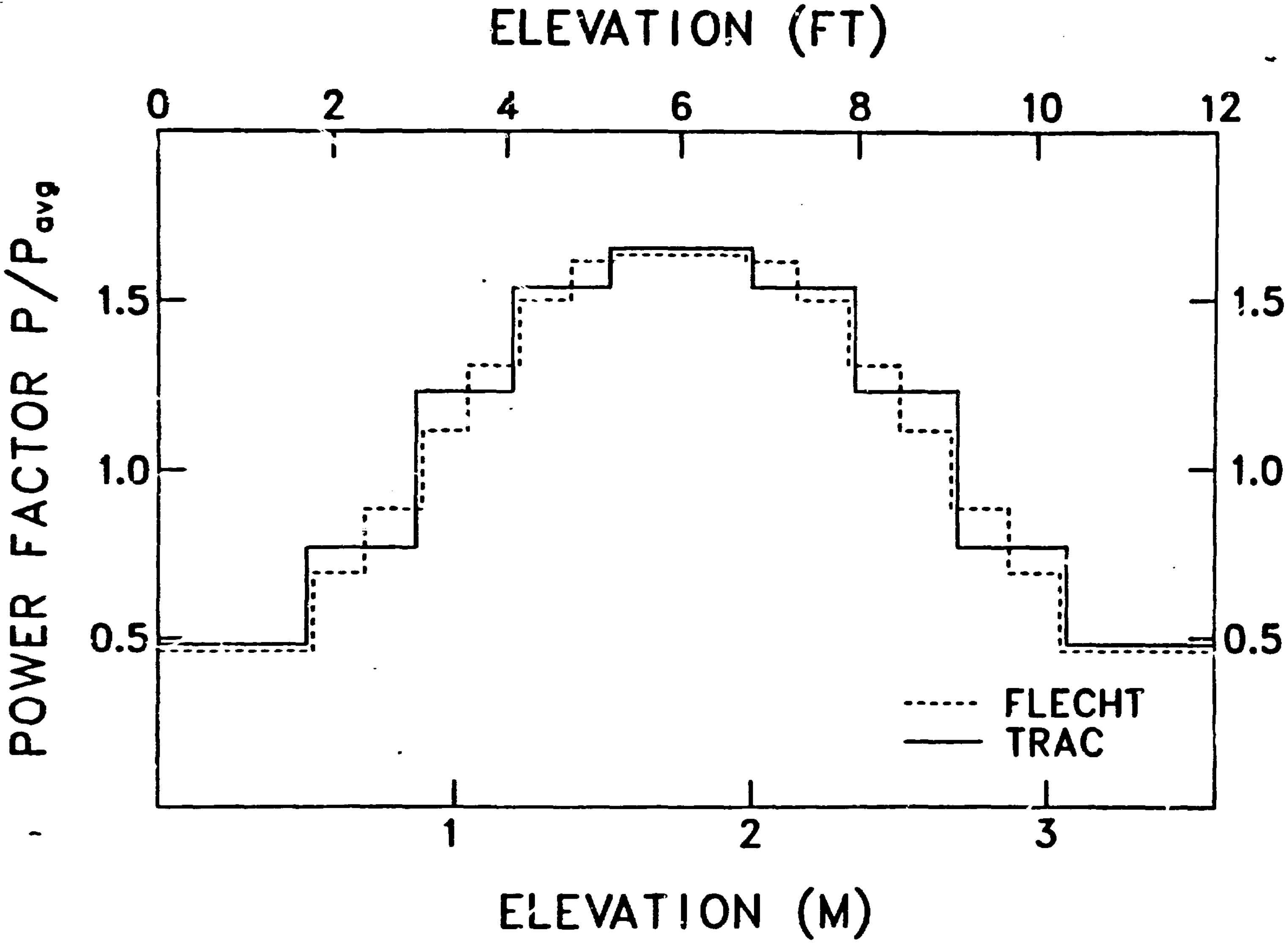

Fig. 2. Axial power profiles for Test 4831.

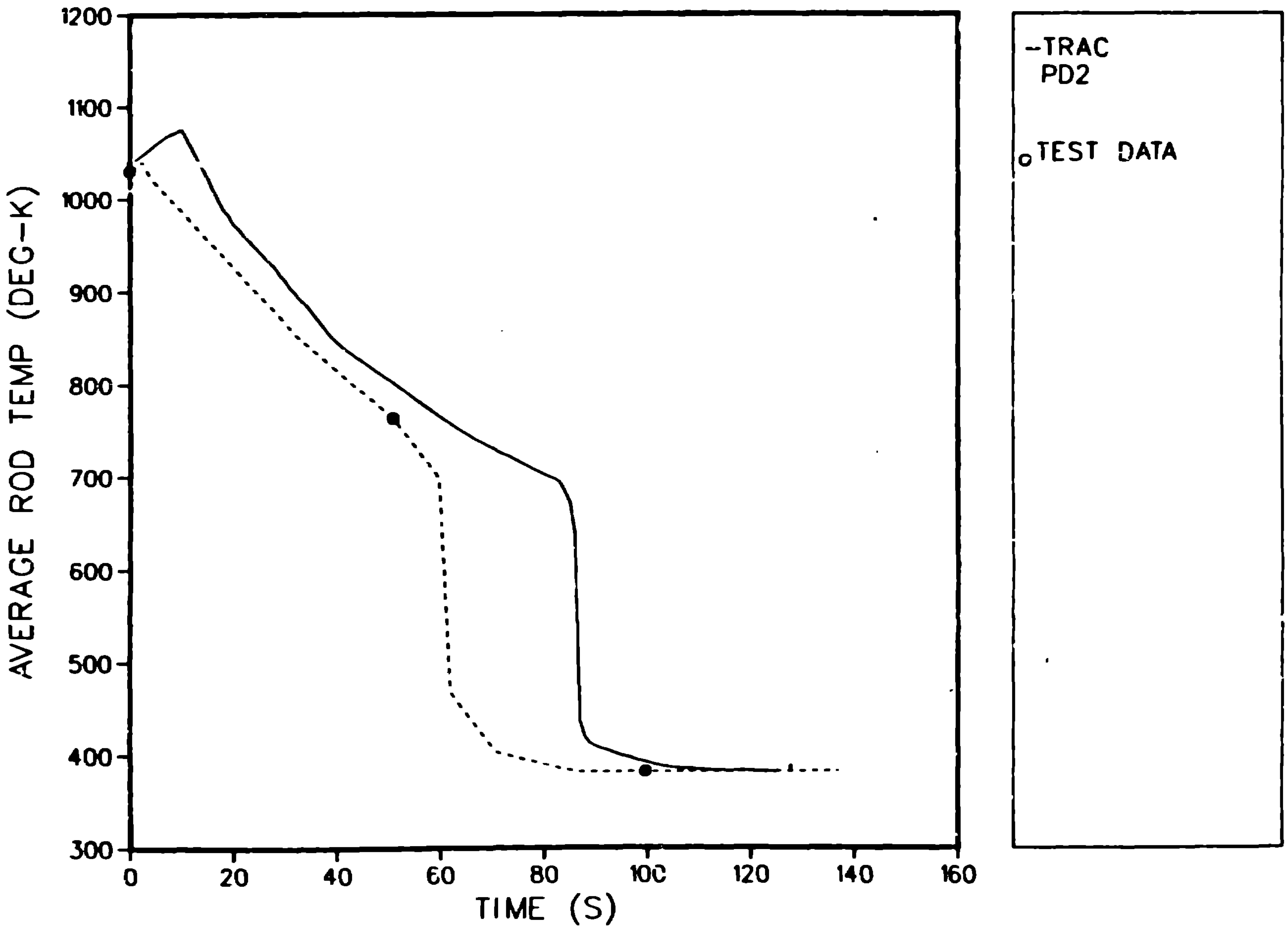

Fig. 3. Test 17201 eight-foot elevation rod clad temperature.

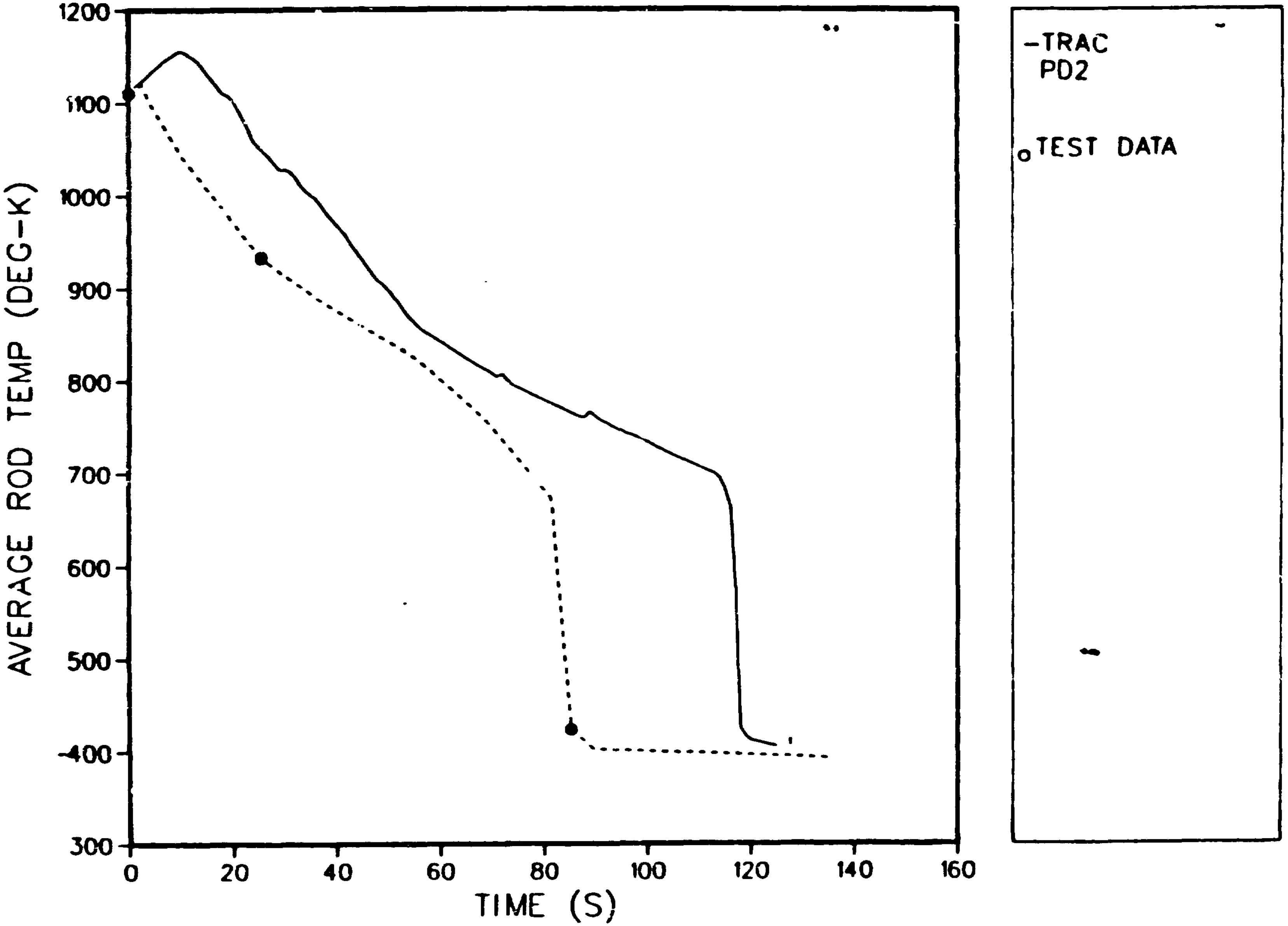

Fig. 4. Test 17201 ten-foot elevation rod clad temperature.

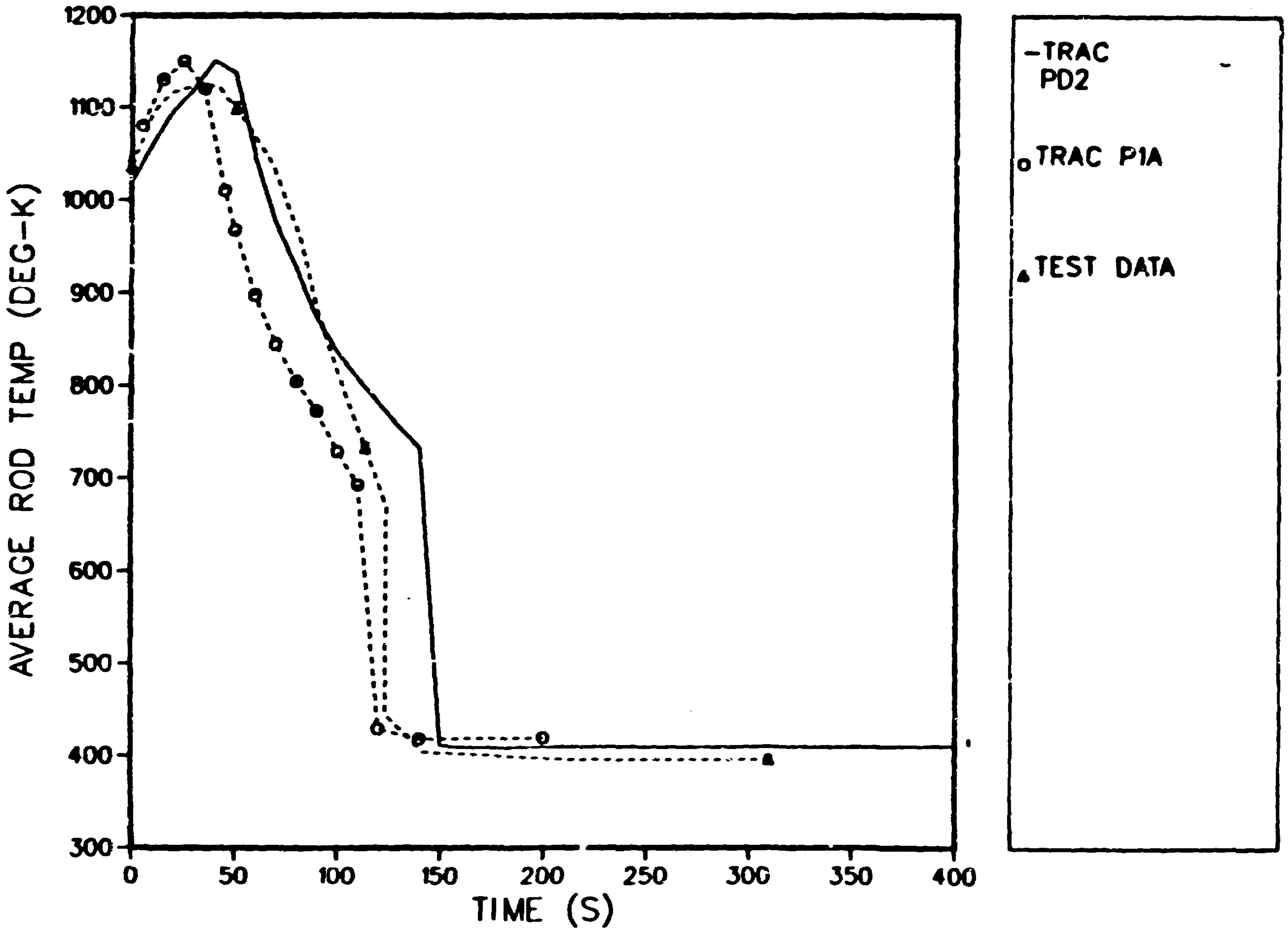

Fig. 5. Test 4831 four-foot elevation rod clad temperature.

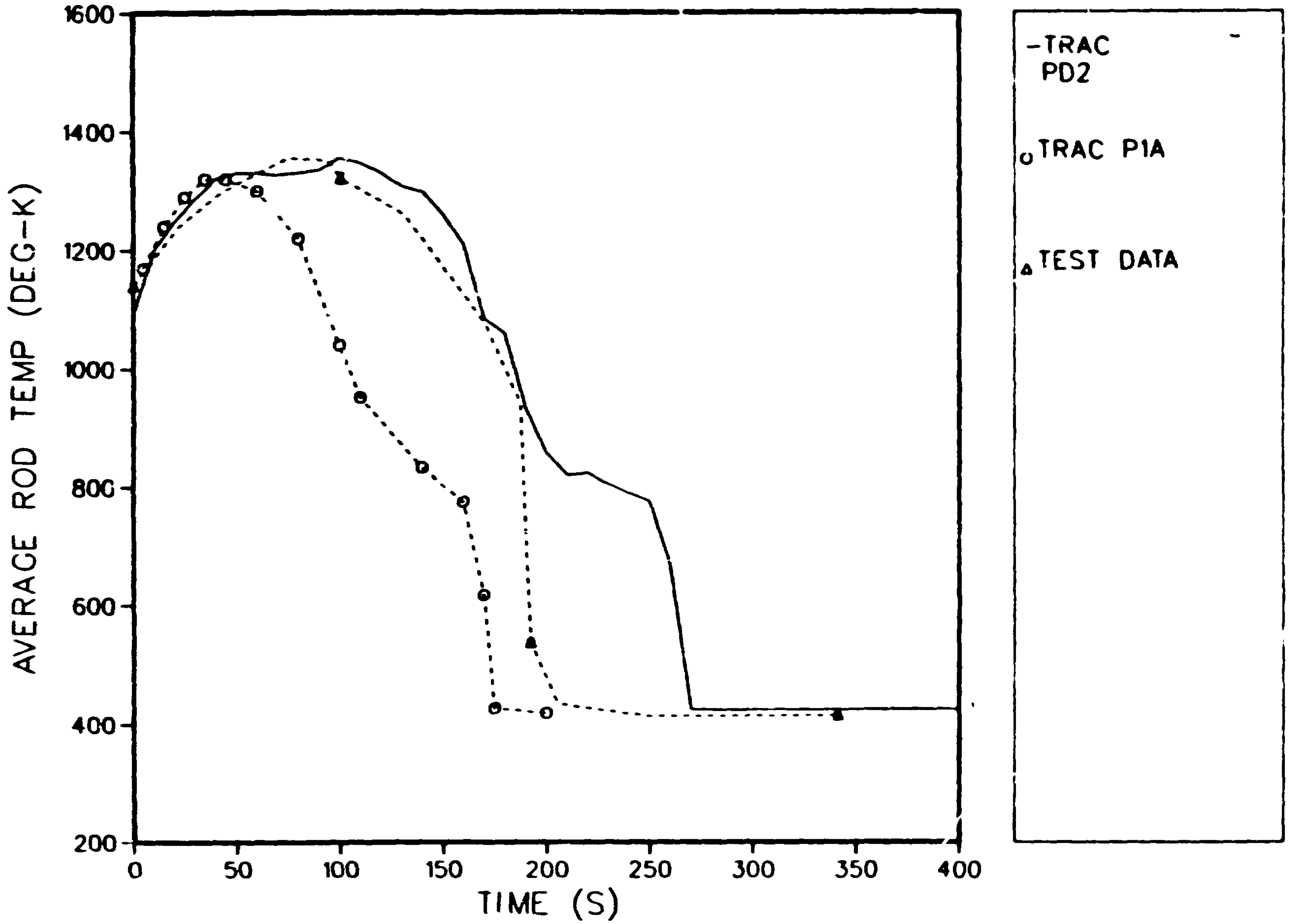

Fig. 6. Test 4831 six-foot elevation rod clad temperature.

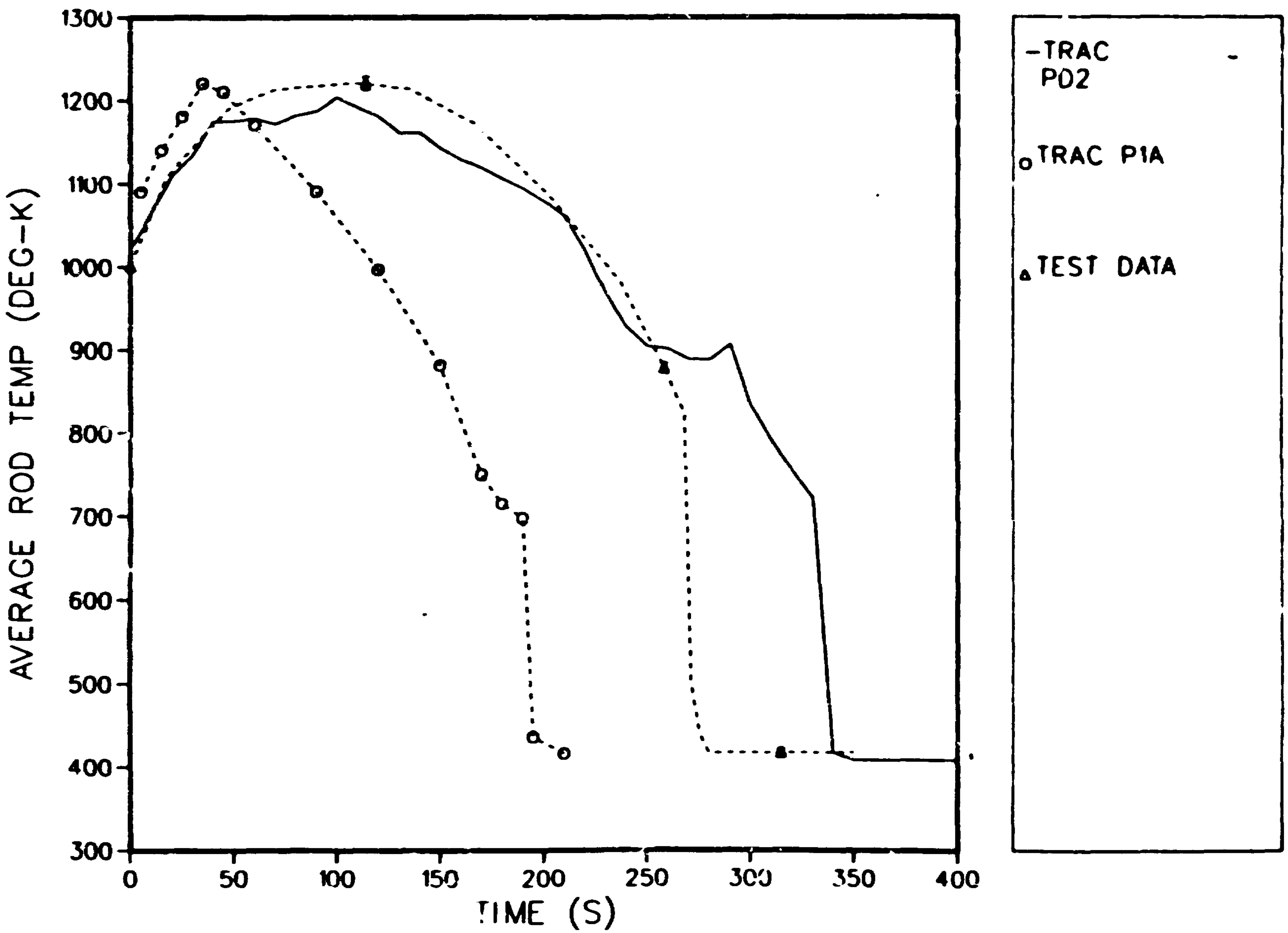

Fig. 7. Test 4831 eight-foot elevation rod clad temperature.

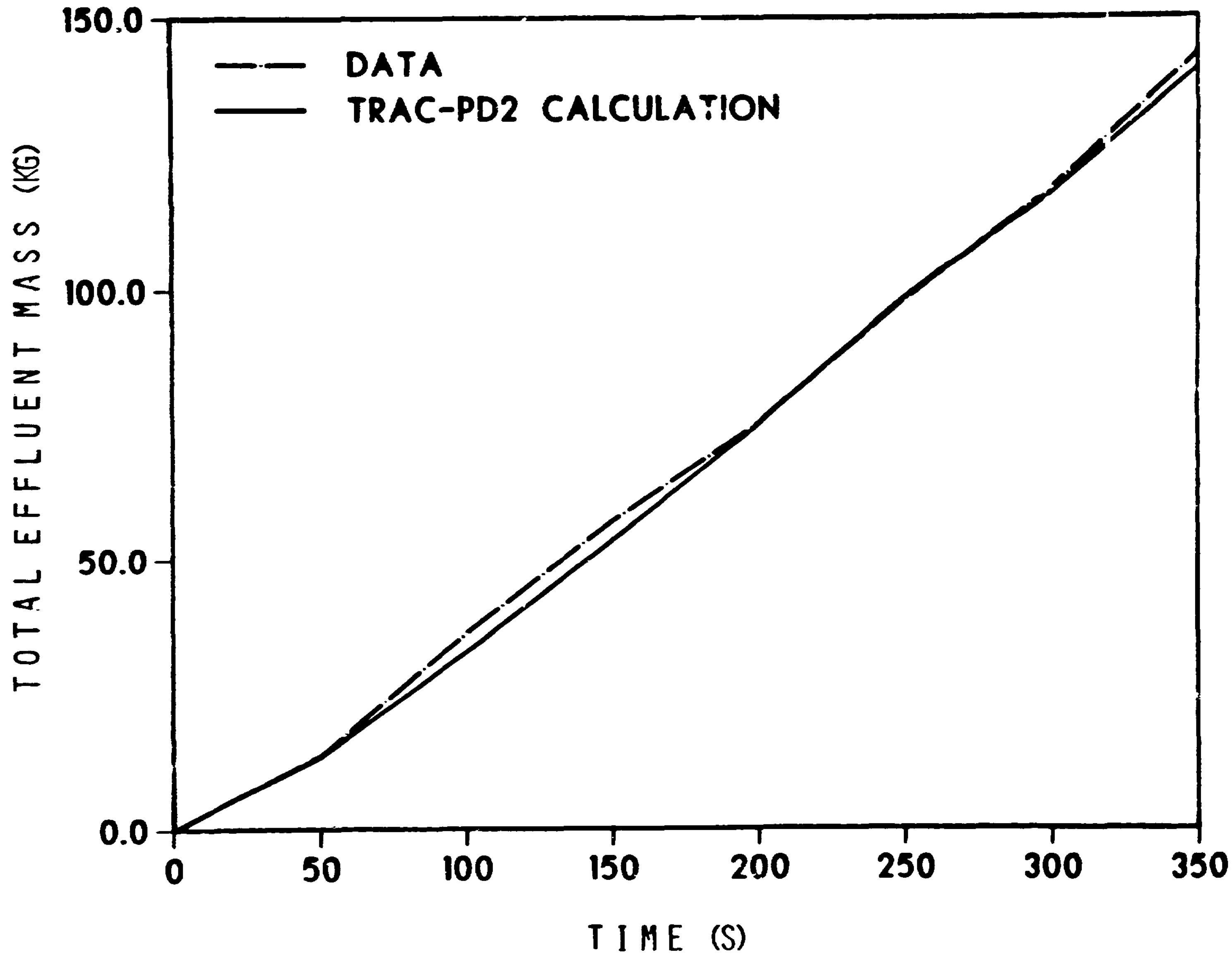

Fig. 8. FLECHT Test 4831 total effluent mass.

TRAC GEOMETRY FOR RADIATIVE HEAT-TRANSFER APPROXIMATION

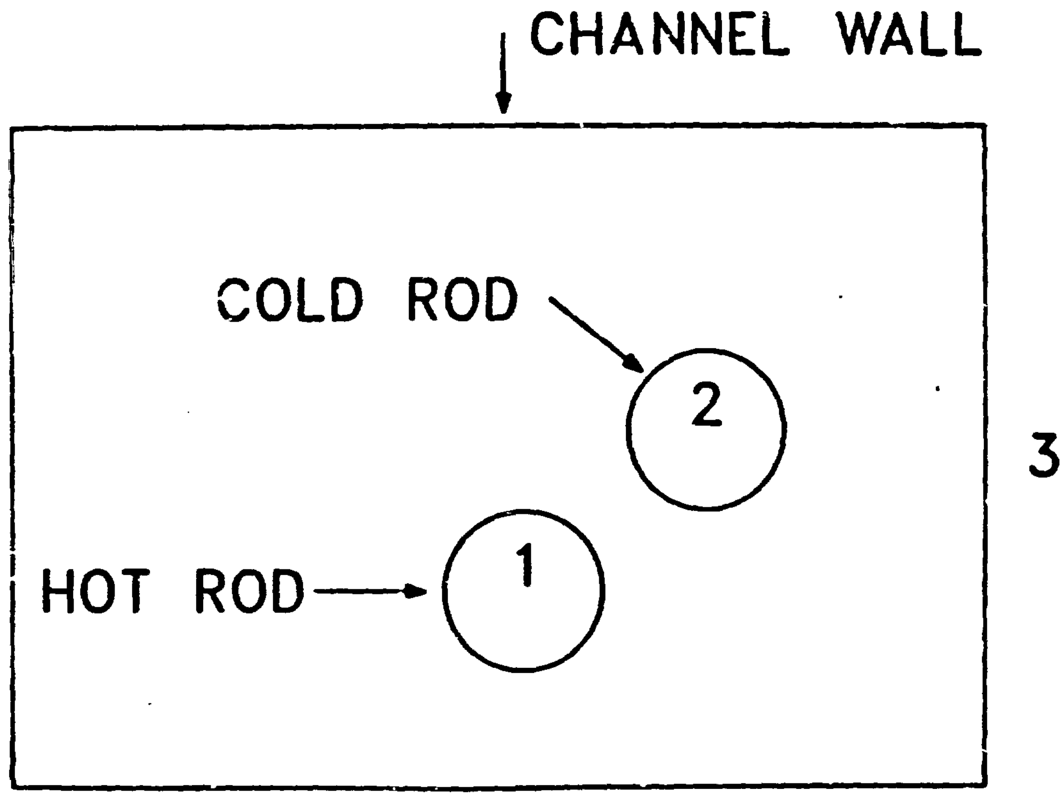

Fig. 9. TRAC geometry for radiative heat-transfer approximation.

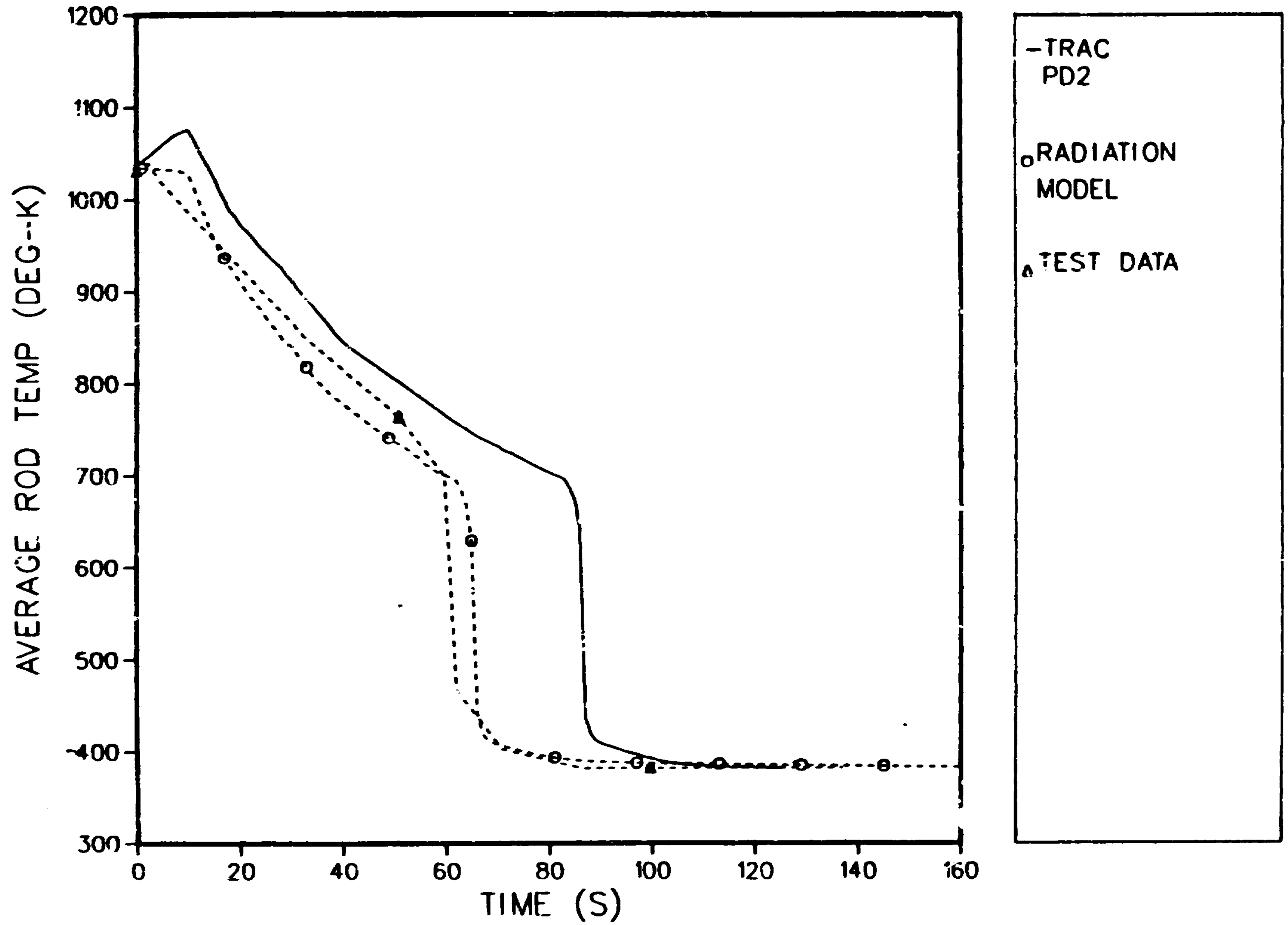

Fig. 10. Test 17201 eight-foot elevation rod clad temperatures with radiation.

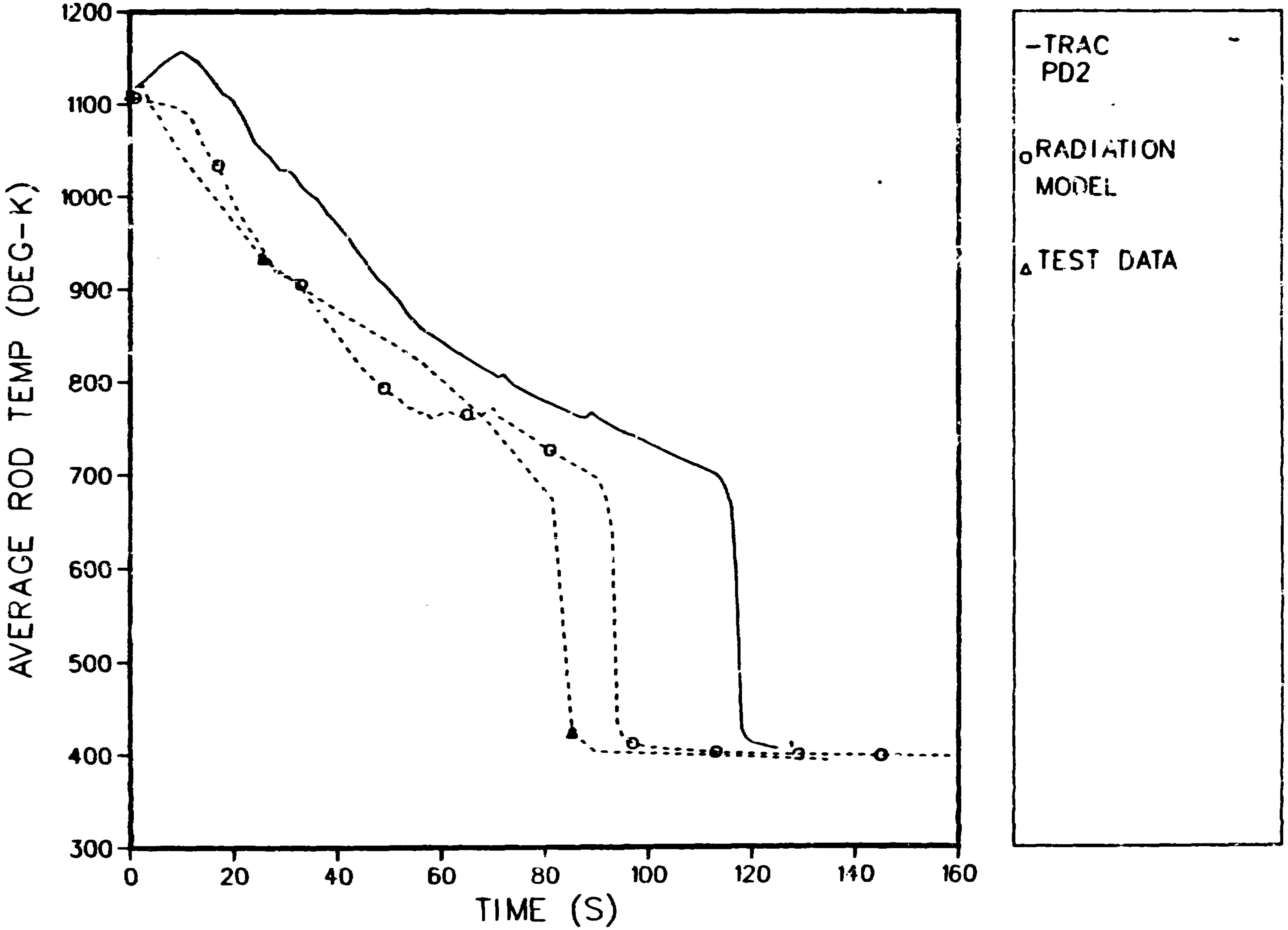

Fig. 11. Test 17201 ten-foot elevation rod-clad temperatures with radiation.

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